Environment Canada
Conservation and Protection

Environnement Canada
Conservation et protection

National Hydrology Research Institute
Institut national de recherche en hydrologie

Inland Waters and Lands Directorate
Saskatoon, Saskatchewan, Canada

Direction générale des eaux intérieures et les terres
Saskatoon, Saskatchewan, Canada

Canada

88-02075/

EXECUTIVE SUMMARY

INLAND WATERS/LANDS DIRECTORATE-WEYERHAEUSER CANADA LTD.

JOINT RESEARCH PROJECT

By

Max L. Bothwell

Environment Canada
Limnological Research Division
National Hydrology Research Centre
11 Innovation Blvd.
Saskatoon, Saskatchewan

PHOSPHORUS CONTROL OF ALGAL PRODUCTION IN THE THOMPSON RIVER, BRITISH COLUMBIA

NHRI Scientific Series
Contribution No. 87002

MAY 1987

UNPUBLISHED VERSION

ACKNOWLEDGEMENTS

This project was jointly funded by Environment Canada and Weyerhaeuser Canada Ltd. Technical support was provided by M. Bolin, S. Jasper, R. Mitchell and K. Suzuki. The site for these experiments was kindly provided by the Village of Chase. The administrative and managerial support and encouragement of R.J. Daley and L. Adamache are gratefully acknowledged.

MANAGEMENT PERSPECTIVE

This document reports the final results of a 4-year study on the effects of nutrients on algal growth and accumulation in the Thompson River, British Columbia. It calls into direct question the efficacy of tertiary treatment (nutrient removal) of effluent as a means of controlling algal production. It appears that in the Thompson River there will not be a one-for-one benefit from nutrient removal. In cases like this one, nearly complete removal will be needed to produce substantial improvement. While the extrapolation of these results to other river systems is partly limited by the hydraulic and physiographic nature of this particular river, similar situations may also exist elsewhere in Canada. These findings question the usefulness of current DOE water quality guidelines for nutrients in rivers and have implications for DOE policy in this area.

It is also apparent that much more needs to be known about the long-term response of rivers to nutrient enrichment before the wisdom of legislating nutrient removal can be properly judged.

PERSPECTIVE-GESTION

Le présent document fait état des résultats finals d'une étude au cours de laquelle, pendant quatre ans, on a examiné les effets des éléments nutritifs sur la croissance et l'accumulation des algues dans la rivière Thompson, en Colombie-Britannique. Il met en cause directement l'efficacité du traitement tertiaire (extraction des éléments nutritifs) de l'effluent comme moyen de lutter contre la production d'algues. Il semble que dans le cas de la rivière Thompson, on ne pourra établir une relation biunivoque entre l'extraction des éléments nutritifs et l'avantage recherché. Dans une situation de ce genre, il faudrait une extraction quasi complète pour produire une amélioration substantielle. Certes, l'extrapolation de ces résultats à d'autres bassins hydrographiques est en partie limitée par la nature hydraulique et physiographique de la rivière examinée, mais il se peut que des situations semblables existent ailleurs au Canada. Ces conclusions remettent en question l'utilité des lignes directrices actuelles du ministère de l'Environnement sur la qualité de l'eau en ce qui concerne les éléments nutritifs dans les rivières, et ont des répercussions sur la politique du MDE en cette matière.

Il appert également qu'il reste beaucoup à apprendre sur la réaction à long terme des rivières à l'apport d'éléments nutritifs avant qu'on puisse juger, en toute connaissance de cause, du bien-fondé de légiférer en matière d'extraction des éléments nutritifs.

RÉSUMÉ

La première phase du programme de recherche en canal expérimental, réalisée conjointement par la Direction générale des eaux intérieures d'Environnement Canada et Weyerhaeuser Canada Ltd. en 1980-1981, a permis d'établir que les niveaux élevés de la biomasse algale dans la rivière Thompson en aval du lac Kamloops étaient attribuables à la présence de phosphore provenant de sources ponctuelles de déversement près de Kamloops. Ces premières comparaisons expérimentales des taux de croissance des algues dans les rivières Thompson nord et sud, ainsi que dans la partie inférieure de la rivière, ont indiqué qu'à des concentrations de phosphore réactif soluble de 3-4 parties par milliard, les algues périphytoniques dans la partie inférieure de la rivière croissaient pratiquement au taux maximal possible pendant la période critique de la fin de l'hiver et du début du printemps.

Dans la seconde phase du programme, menée à Chase (C.-B.) au cours de la période 1984-1986, on a effectué des expériences détaillées sur des additions contrôlées de phosphore. Ces expériences ont clairement démontré que les taux de croissance des diatomées périphytoniques dans la rivière Thompson atteignent le point de saturation à des concentrations très faibles de phosphate (moins de 1 partie par milliard). Des expériences sur l'accumulation de la biomasse algale à long terme, aussi réalisées au site expérimental de Chase, ont montré que la biomasse algale maximale atteinte dans des eaux en écoulement

présente également une cinétique de saturation. Toutefois, les concentrations de phosphate requises pour mener au point de saturation la culture sur pied maximale pouvant être maintenue sont de beaucoup supérieures (environ 5-25 parties par milliard) à celles qui saturent le taux de croissance cellulaire. Malgré la réponse continue de la biomasse algale à l'augmentation des niveaux d'addition de phosphore, la forme de la courbe de saturation de la biomasse montre qu'on ne peut s'attendre à ce qu'il existe une relation biunivoque entre l'extraction du phosphore et la réduction de la quantité d'algues.

En supposant que la concentration moyenne de phosphore directement disponible dans la partie inférieure de la rivière Thompson est accrue par l'effluent de l'usine de pâte à papier d'environ 2,5 parties par milliard pendant la période de faible débit, on peut prévoir approximativement la réponse, en aval, de la biomasse algale qui pourrait résulter d'un pourcentage donné de réduction de la charge en phosphore. Une simple analyse des données sur la biomasse algale maximale pouvant être maintenue en réponse à des additions de phosphate révèle qu'une réduction de 50 % du phosphore provenant de l'effluent de l'usine procurerait une amélioration de moins de 20 % en aval. Pour obtenir une amélioration "significative" en aval, c.-à-d. une réduction de 60 % de la biomasse algale, il faudrait extraire au moins 90 % du phosphore soluble disponible dans l'effluent. Ce résultat montre qu'il ne serait pas rentable de déployer des efforts additionnels pour extraire le phosphore de l'effluent de l'usine, dans

l'intention de lutter contre la formation d'algues en aval. En outre, selon des observations faites récemment, le degré de "nuisance" des algues qu'on signalait dans les années 70 n'est plus le même aujourd'hui, de sorte qu'il ne serait peut-être même pas justifié de prendre d'autres mesures de contrôle des éléments nutritifs dans l'avenir.

ABSTRACT

The first phase of the experimental trough research program undertaken jointly by the Inland Waters Directorate of Environment Canada and Weyerhaeuser Canada Ltd. during 1980-1981, established that the higher algal biomass levels in the Thompson River downstream of Kamloops Lake were caused by phosphorus originating from point source discharges near Kamloops. These early experimental comparisons of algal growth rates in the North, South and lower Thompson Rivers indicated that at soluble reactive phosphorus concentrations of 3-4 ppb, periphytic algae in the lower Thompson River were growing at or near the maximum rate possible during the critical late winter-early spring period.

The second phase of the program consisted of extensive controlled phosphorus addition experiments conducted at Chase, B.C. during 1984-1986. These experiments have conclusively established that the growth rates of periphytic diatoms in the Thompson River saturate at very low phosphate concentrations (at less than 1 ppb). Long-term algal biomass accumulation experiments, also conducted at the Chase experimental site, have shown that the maximum biomass of algae attained in flowing water also shows saturation kinetics. However, the concentrations of phosphate required to saturate the maximum

sustainable standing crop of algae are considerably higher (about 5-25 ppb) than those which saturate cellular growth rate. In spite of continued algal biomass response with higher levels of P-addition, the shape of the biomass saturation curve means that a one-for-one, removal of phosphorus vs. reduction of algae, is not expected.

Assuming that the average concentration of readily available phosphorus in the lower Thompson River is elevated by the pulpmill effluent by about 2.5 ppb during the low flow period, it is possible to roughly predict the downstream response in algal biomass which might result from a given percentage reduction in P-loading. Using data on the maximum sustainable algal biomass in response to phosphate additions, a simple analysis indicates that a 50% reduction in phosphorus from the mill effluent would result in less than a 20% improvement downstream. In order to achieve a "significant" improvement downstream, ie. a 60% reduction in algal biomass, at least 90% of the available soluble phosphorus in the effluent would have to be removed. This finding suggests that additional efforts to control downstream algae by removing phosphorus from the pulpmill effluent would be relatively ineffective. Furthermore, recent observations that the "nuisance" levels of algae reported in the 1970's are no longer present, suggest that additional nutrient control measures in the future may not even be warranted.

HISTORICAL BACKGROUND

Following commencement of operations at the Weyerhaeuser Canada Ltd. pulpmill in Kamloops in the late 1960's, numerous complaints from both the general public and fisheries biologists about water quality degradation problems in the Thompson River below Kamloops Lake were voiced. The three primary areas of concern were: 1) taste and odour problems in fish flesh, 2) colouring and foaming in the river and 3) massive accumulations of algal slime on the rocks. A Federal-Provincial Task Force established in 1973 to address these questions concluded that the first two of these concerns were either not well supported by sound scientific facts or were primarily of an aesthetic nature, ie. they did not appear to be of major ecological importance. The algal growth problem, however, was well-documented scientifically and potentially a risk for both fishermen (slippery rocks) and fish. The Task Force's final report in 1976 identified phosphorus loadings from both the Weyerhaeuser pulpmill and the City of Kamloops municipal sewage discharges as responsible for the high levels of algae in the lower Thompson River. Therefore in 1976, the City of Kamloops began practicing winter holdback and tertiary treatment of their effluent. These actions effectively reduced by at least one-half the point source phosphorus loadings to the Thompson River. Although the algal blooms below Kamloops

Lake diminished somewhat in the late 1970's and early 1980's, the problem still persisted.

The Task Force presented strong and compelling evidence that phosphorus was the cause of the algal infestations. However, the arguments were indirect and circumstantial. In 1976, no evidence was available which directly proved that periphytic algae in the Thompson River downstream of the P-inputs were either physiologically more phosphorus rich or whether they were in fact actually growing faster than algae at upstream locations. These two central questions needed to be affirmed before a reasonably conclusive judgement could be made that the algal slime accumulations in the lower Thompson River in the early 1970's were the result of point source P-loadings from the Kamloops area.

In 1979, experiments were proposed to answer these two key questions. An agreement for a jointly funded research project between Environment Canada's National Water Research Institute and Weyerhaeuser Canada Ltd. was reached in the fall of 1979. The research conducted during the winters of 1980 and 1981 involved the use of experimental troughs located on the banks of the North, South and lower Thompson rivers. These troughs simultaneously compared algal growth rates and phosphorus physiology in the three rivers under controlled physical conditions. The results of these experiments confirmed the

conclusion in the 1976 Task Force report, ie. that phosphorus was in fact responsible for the excessive algal accumulations in the Thompson River. They showed for the first time that 1) soluble phosphorus concentrations downstream of Kamloops Lake were consistently higher than in the two upstream tributaries and 2) that the periphyton algae downstream were physiologically responding to the higher phosphorus levels and were growing faster.

In spite of establishing a strong connection between P-loading and the algal problem downstream, it was still not possible in the early 1980's to predict the amount of improvement (reduction in algal biomass) to expect from a given reduction in the loading. (The one obvious exception to this is if anthropogenic P-loading were to be eliminated entirely. In this case the improvement would be 100%, ie. all other factors being equal downstream amounts of algae should be no different than before the advent of the cultural enrichment.) One reason for the difficulty in predicting downstream response to partial P-removal is that the relationship between algal growth rate and phosphorus concentration in flowing waters is a rectangular hyperbola. Such saturation curves characterize most types of biological responses. A cost-benefit analysis for removal of phosphorus from the Weyerhaeuser Canada pulpmill first required that the shape of these curves be established. To this end another agreement for cooperative research was

negotiated between Environment Canada and Weyerhaeuser Canada Ltd. in 1983. This new contract funded sophisticated phosphorus addition experiments conducted between 1984 and 1986 at the experimental troughs research apparatus near Chase, British Columbia (Figure 1).

This report summarizes the main findings of this final phase of the research project on phosphorus control of algal production in the Thompson River. Only those experiments and data germane to assessing the efficacy of tertiary treatment (P-removal) of the Weyerhaeuser Canada effluent, as a means of ameliorating the Thompson River algal "problem" downstream of Kamloops Lake, will be presented. Although an attempt has been made to discuss the results in lay terms, the use of some scientific and technical jargon is unavoidable. A glossary of the technical terms frequently used in this report is provided at the back.

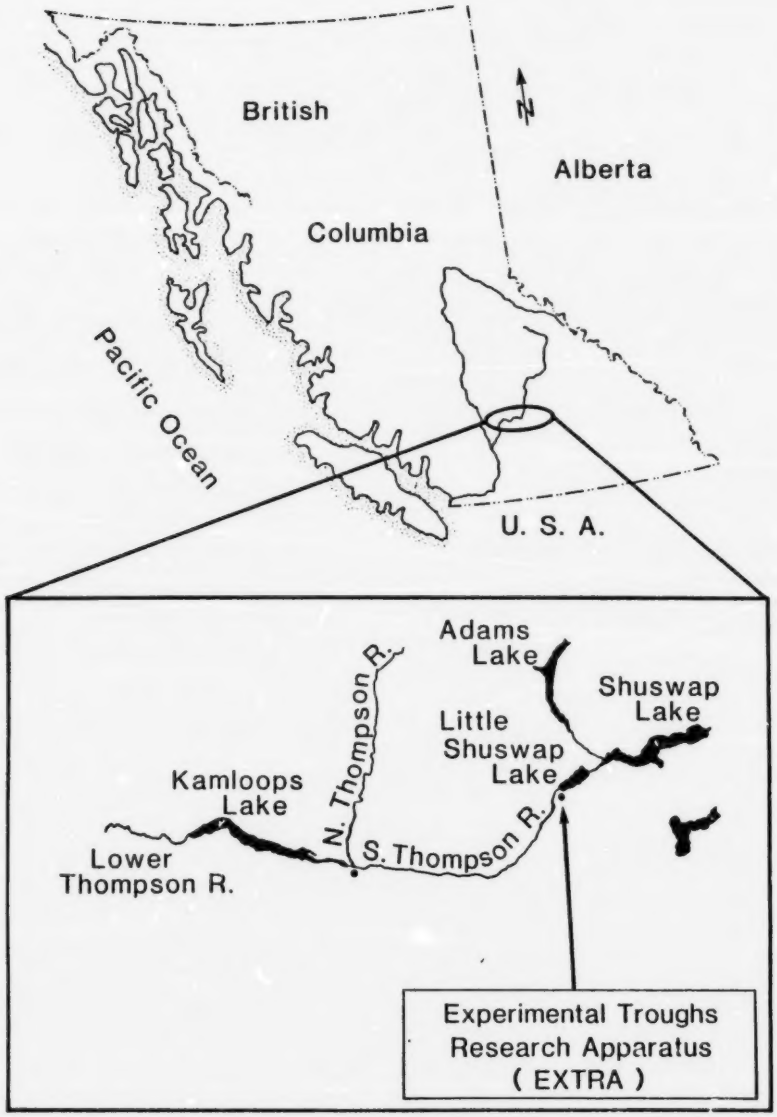

Figure 1. Map showing the location of the experimental troughs research apparatus (EXTRA) near the outlet of Little Shuswap Lake in south central British Columbia.

RESULTS AND DISCUSSION

Periphyton algal growth rates

One of the primary conclusions from the intersite comparison experiments conducted in 1980-1981 was that growth rates of periphyton algae saturate at low phosphate concentrations (Bothwell 1985). This conclusion was drawn on the basis of a limited number of observations and without precise knowledge of what the actual concentration of orthophosphate was in the rivers. Nevertheless, based largely on physiological evidence (alkaline phosphatase activity (APA), cellular N:P and C:P ratios) algae in the lower Thompson River appeared to be growing at or near maximal rates even though soluble reactive phosphorus levels were only 3-4 ppb.

This conclusion from the earlier research has now been confirmed and proven to be correct beyond any doubt. In fact, the levels of phosphate which saturate growth rate are actually much lower than previously expected. In ten separate experiments during 1984-1985 using enrichment levels of 0.1, 0.2, 0.5, 1.0, 2.0 and 5.0 ppb of orthophosphate-P the specific growth rates (u = divisions per day) of the algal communities always saturated at less than 1.0 ppb. The rectangular hyperbolic nature of the growth rate vs. P-concentration curves

at different times of the year is clearly apparent (Figure 2). While all curves saturate at low phosphorus concentrations, the maximum growth rate at different times of the year varied. The seasonal differences in the maximum rate are largely determined by temperature, ie. at higher temperatures, growth rates with elevated levels of phosphorus are higher (Figure 2).

If the growth rates (u) are normalized to the maximum growth rate (u_{max}) observed in each experiment and plotted against P-concentration, all the curves appear to be the same throughout the year (Figure 3). The fact that the relative specific growth ($u:u_{max}$) response of algae to P-enrichment is similar year-round reaffirms that normalizing u to u_{max} factors out the major effects of physical factors controlling growth rate.

Phosphorus control of algal biomass

The majority of the experiments have focused on the effect of phosphorus on algal growth rates. The reason for this was the belief that the only way for a nutrient like phosphorus to affect changes in the biomass of algae in a river was to do so by altering their growth rates. Still, the primary motivation for this study was to find out how phosphorus influenced algal biomass. To test this directly, three long-term studies were

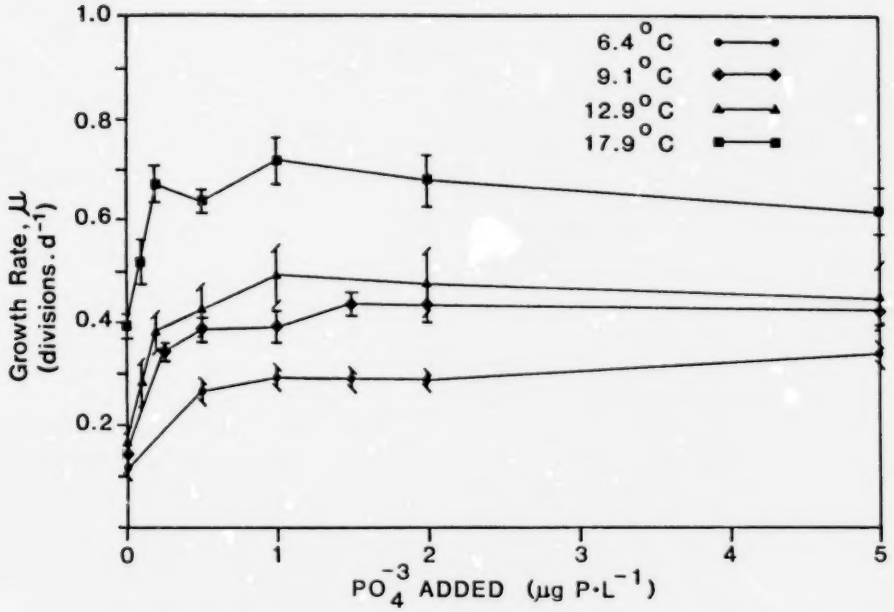

Figure 2. Growth rate (u) of South Thompson algae in divisions per day versus added phosphate concentration at different temperatures (ie. different times of the year).

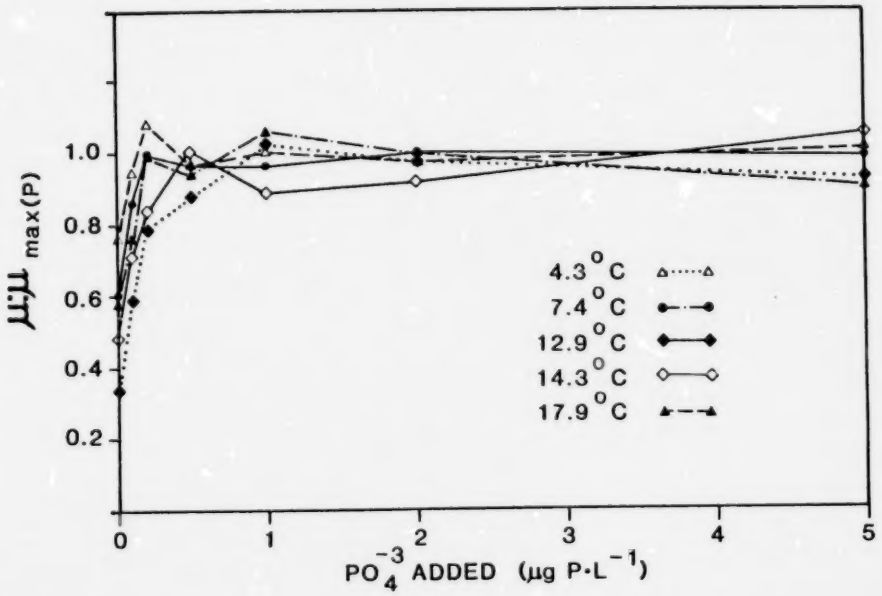

Figure 3. Relative specific growth rate of South Thompson algae versus added phosphate concentration at different temperatures (ie. different times of the year).

conducted to see how maximum sustainable biomass in flowing troughs would be influenced by phosphorus concentration and to see if this relationship differed substantially from the phosphorus-growth rate relationships.

Figure 4 shows the actual time course changes in algal biomass during one of the long-term (60 days) experiments (Oct-Dec, 1984). In these trials biomass increased exponentially for a period of about two weeks, reached a peak and then usually began to slowly decline. The relationship between P-concentration and biomass was assessed in three different ways: 1) the maximum biomass attained at each P-treatment, 2) data from the inflection point to the end of the experiment were averaged and 3) biomass data from Day 35 to the end of the experimental period were averaged. All three methods gave relatively similar results. The data used in this report are average values from Day 35 to the end of each trial (about Day 60). These values were taken to approximate the maximum sustainable algal biomass (MSB) levels.

The validity of these biomass vs. P-concentration experiments is strengthened by the fact that the curves show saturation at higher P-levels (Figure 5). As with the growth rate plots, different curves were obtained at different times of the year. Two basic curves were obtained: one for periods of

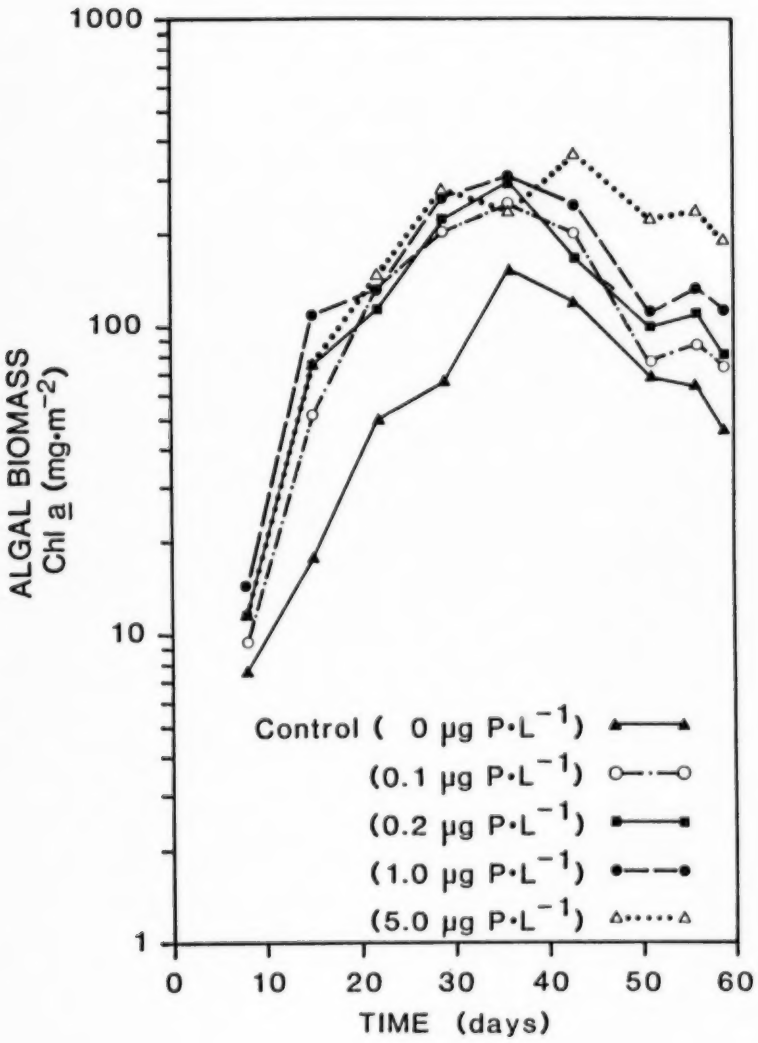

Figure 4. Time course curves of periphyton biomass at different phosphate additions during one of the long-term experiments (Oct-Dec 1984).

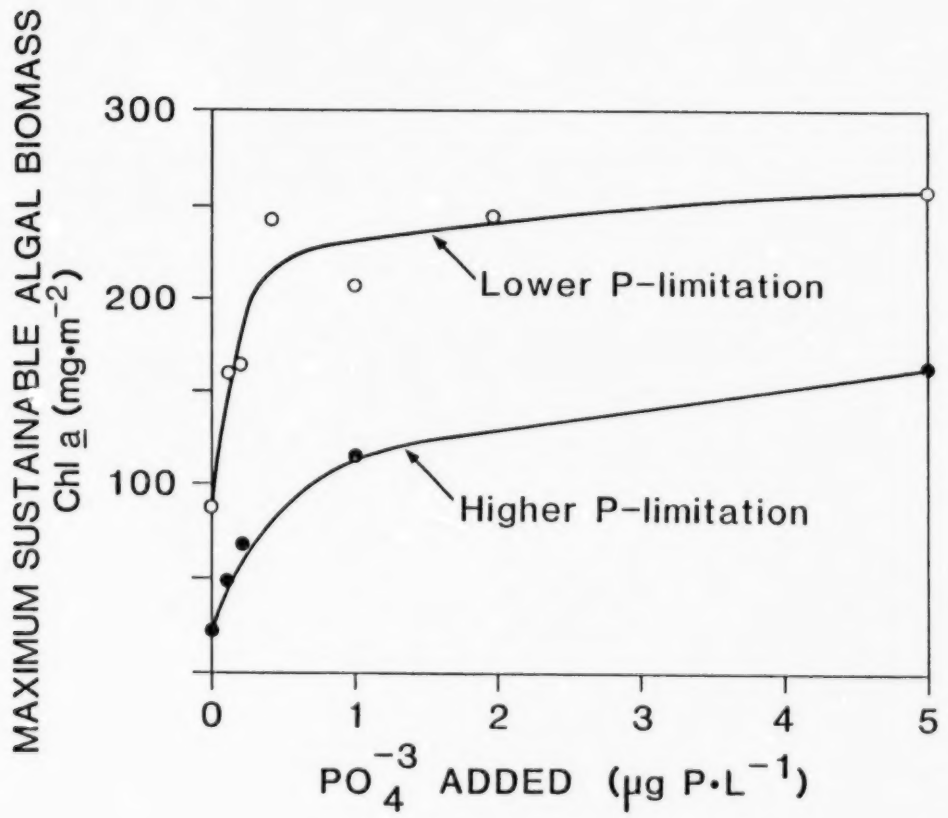

Figure 5. Maximum sustainable algal biomass (MSB) in response to phosphate additions during experiments when the river was highly phosphorus limited (Feb-Mar) and when it was less phosphorus limited (Oct-Dec).

higher P-limitation (Feb-Mar) and another for periods of lower P-limitation (Oct-Dec). The degree of phosphorus limitation was judged from the levels of alkaline phosphatase activity (APA) in the control algae. These biomass curves differ from the growth rate curves in one very important respect: they do not saturate at low phosphorus levels. Biomass continues to increase up to 5 ppb and beyond. In one experiment (Oct-Nov 1985) where concentrations of phosphate-P all the way to 100 ppb were used, biomass continued to respond up to 25 ppb (Figure 6A). When these same data are plotted on a semi-log scale (Figure 6B) a log-linear relationship between phosphorus concentration and MSB is apparent; with saturation occurring just above 25 ppb.

There are two possible explanations for the fact that MSB saturates at much higher P-concentrations than specific cellular growth rates. One or both of these factors may be operating: 1) The growth rate experiments were intentionally conducted at low biomass levels (usually well under 100 mg Chl $a \cdot m^{-2}$) to minimize the possibility that sloughing would influence the results. During the long-term biomass studies however, algal densities were usually much greater 100-300 mg Chl $a \cdot m^{-2}$. Intuitively, thicker algal mats require greater concentrations of phosphorus to saturate growth of the mat as a whole. 2) Small changes in the specific growth rate will translate into large differences in biomass over long periods

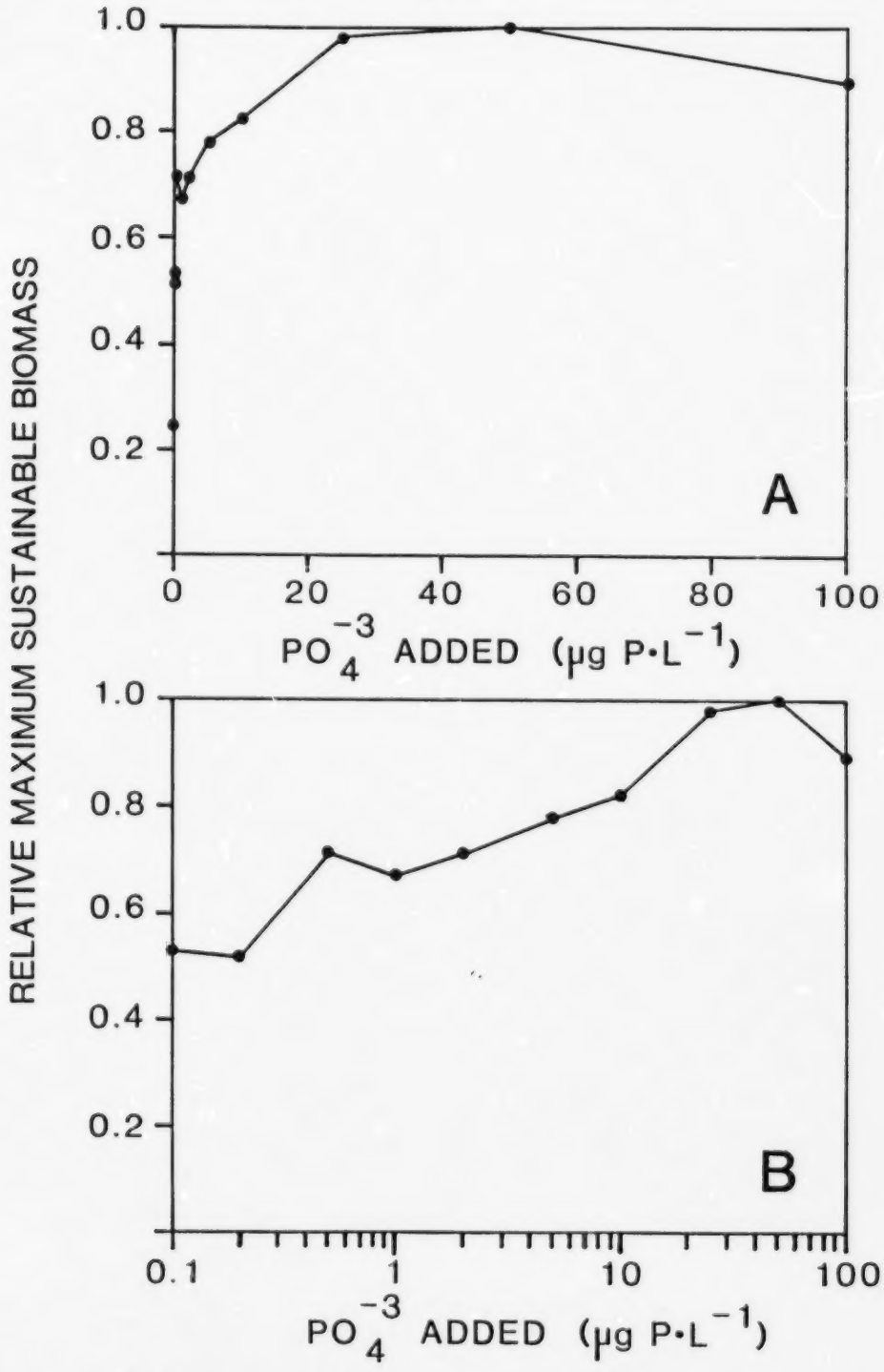

Figure 6. Relative maximum sustainable algal biomass ($MSB:MSB_{max\text{-}P}$) in response to phosphate additions up to 100 ppb during a long-term experiment (Oct-Nov 1985). A. Phosphate additions are plotted on a linear scale. B. The same data as in A. but the phosphate values are plotted on a log-scale.

of time. Hence, while additional increases in u may seem insignificant, they might well result in measurable differences in biomass accumulated over longer periods of time.

Seasonality of phosphorus limitation

One problem posed by the fact the response of $u:u_{max}$ to P-additions shown in Figure 2 appears to be the same year round is that it suggests that the background concentrations of dissolved phosphorus in the South Thompson River do not vary seasonally. This is at odds with measurements in 1980-81 of soluble reactive phosphorus (SRP) and total dissolved phosphorus (TDP) in the Thompson River system as well as periphyton APA data, all of which indicated lower amounts of available phosphorus during the spring than in the winter (Bothwell and Daley 1981; Bothwell 1985). Although SRP concentrations in the South Thompson at Chase during 1984-85 showed no consistent seasonal change (data not shown), the APA data did show distinct trends consistent with the earlier observations indicating much higher phosphorus deficiency during the late winter through summer than during the fall and early winter (Figure 7).

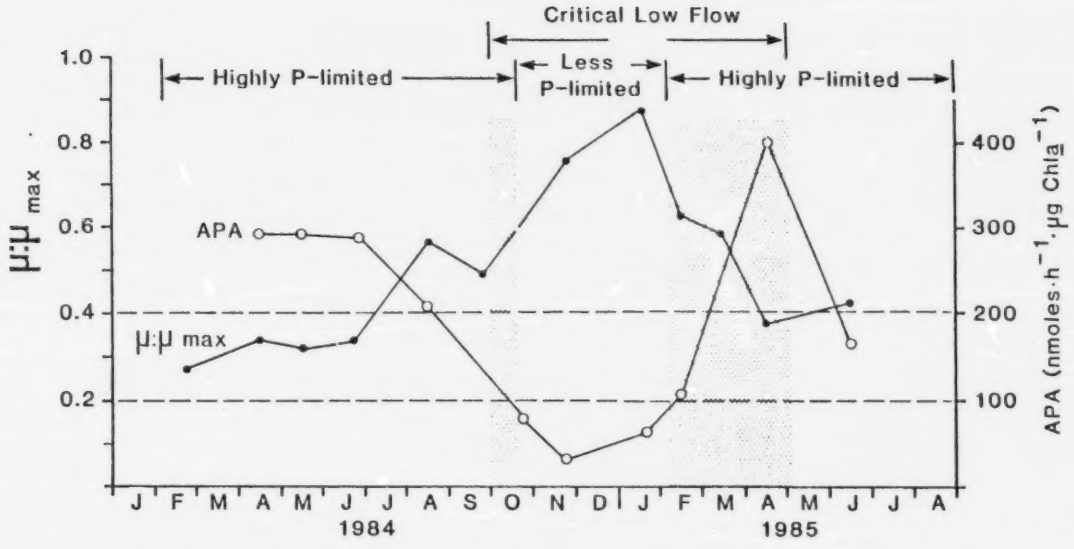

Figure 7. Seasonal changes in relative specific growth rates and alkaline phosphatase activity (APA) in the South Thompson River periphyton algae. The critical low-flow period of the year and the times of high phosphorus deficiency are outlined. Shaded areas mark those times of the year when these two conditions overlap.

The seeming paradox presented by Figure 3 suggesting that the available background P-content in the South Thompson River is the same at different times of the year and the APA data in Figure 7 indicating exactly the opposite, is the result of the scale on which the data in Figure 3 are plotted. The relative growth rate responses to addition of very low levels of phosphate in fact differ throughout the year. This is clearly shown graphically in Figure 8. Here the $u:u_{max}$ values for 1984-85 are shown for only the control and the lowest levels of P-addition. The relative specific growth rate of algae in the control trough (with no phosphorus added) varies seasonally. Maximum values, indicating low phosphorus deficiency, occur during fall and midwinter while low values (high phosphorus deficiency) are present in late winter through summer. When the algae are not very P-limited, the addition of very small amounts of phosphate (less than 0.1 ppb) results in growth rate saturation. Under more phosphorus limited conditions additions of 0.5 ppb or higher of phosphate are needed to saturate growth rates (Figure 4). This means that background levels of readily available phosphorus in the South Thompson River vary seasonally. Data from the earlier 1980-81 intersite comparison (Bothwell and Daley 1981; Bothwell 1985) suggested similar seasonal changes occur in the North Thompson River as well. This information is important in determining those times of the year when river algae will respond the most to P-loading.

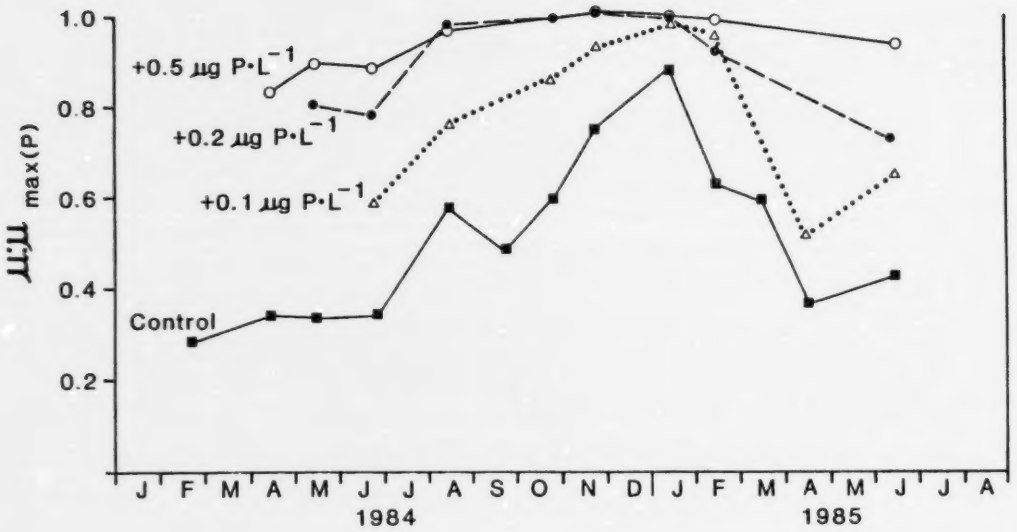

Figure 8. Relative specific growth rates of algae throughout the year at different levels of phosphate addition.

APA data from the control algae can be used as an indicator of the degree of phosphorus deficiency in the river. Taking values of less than 100 nmoles·h^{-1}·ug Chl a^{-1} as being indicative of low P-deficiency, the period from approximately October through January would show less response to P-loading than at times of the year when APA exceeds 100, ie. from roughly February through August (Figure 8). The exact timing of these periods varies from year to year but the general pattern remains the same.

Another major factor affecting algal accumulation in rivers is water flow. Usually algae in the Thompson River accumulate and become a problem only during periods of low, stable flow. Furthermore, at low flows the elevation in P-concentration from point source loadings will be higher by virtue of lower dilution. The critical low flow period in the Thompson River is usually from October through April (Figure 7). The time intervals when critical low flow coincides with periods of high phosphorus deficiency are indicated by the shaded areas in Figure 7. There are two periods each year when the river is most sensitive to phosphorus pollution: one, a short period in fall (October) and another longer period from February through April.

Prediction of algal response to P-control measures

The amount of algae on rocks in the river is the main issue for environmental managers concerned with nutrients and eutrophication. Because of the discrepancy between the responses of growth rate and areal biomass to P-additions, only the MSB curves will be used here in predicting the potential effects on algal biomass in the river resulting from P-removal from the Weyerhaeuser Canada discharge.

As seen in Figure 5, different MSB curves were obtained during periods of high and low phosphorus limitation. This difference persists even if the biomass data are normalized to the maximum amount of algae observed in the highest P-treatment in each trial (MSB_{max-P}; Figure 9). When these two relative biomass response curves ($MSB:MSB_{max-P}$) are plotted on a semi-log scale the difference between the rates of response under high and low P-deficiency are obvious (Figure 10). The algae are much more sensitive to P-loading when they are more P-deficient. Therefore, only the data set from the period of high P-limitation will be used. This should liberally estimate the effects of the loading on the river at other times of the year.

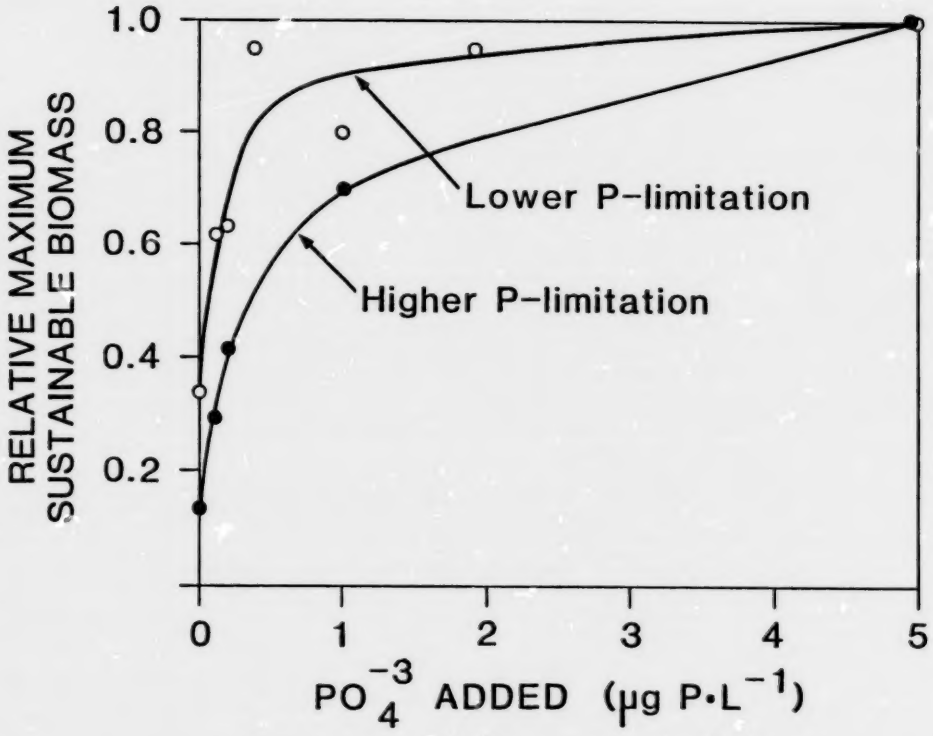

Figure 9. Relative maximum sustainable biomass (MSB:MSB_{max-P}) versus phosphate addition during long-term experiments conducted during periods of high and low phosphorus deficiency in the river.

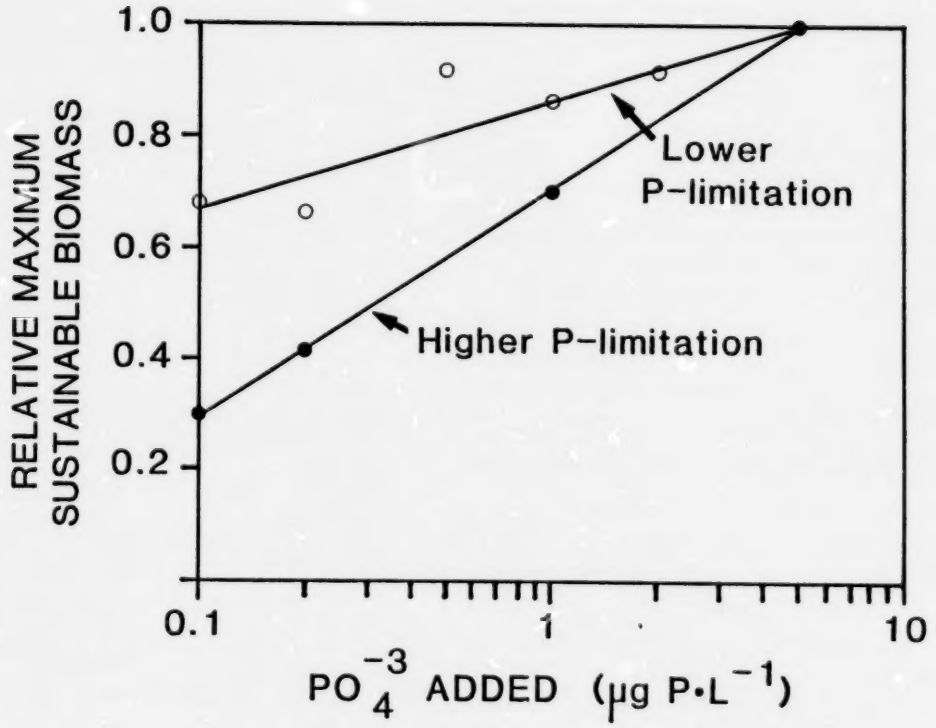

Figure 10. The same data on relative MSB response to phosphate additions shown in Figure 9 but here plotted on semi-log scale.

Prerequisite to estimating the effect of potential reductions of phosphorus loadings to the river is knowledge of what the present discharge is adding. Figure 11 shows the calculated dilution curve of the kraft mill effluent (KME) in the Thompson River using an assumed constant effluent discharge of 1.68 $m^3 \cdot s^{-1}$ (J. Zagar pers. communication) and mean monthly flow data for the Thompson River at Spences Bridge (Environment Canada 1983). Estimates of the concentrations of readily available dissolved phosphorus in the KME from both chemical measurements and radiobioassays are around 300 ppb (Jasper and Bothwell 1986). Using values of 300 ppb for the SRP content of the KME and the dilution curve in Figure 11, the calculated increase in available soluble phosphorus concentration in the Thompson River is shown in Figure 12. The computed increases in SRP during low flow closely match the increases observed in the lower Thompson River during the winter of 1980-81 (Figure 12; Bothwell 1985). Keeping in mind the variation and measurement errors in all the above parameters as well as the many simplifying assumptions made in this computation, the best estimate is that during annual low flow the present KME discharge elevates the SRP content of the Thompson River by approximately 2.5 ppb.

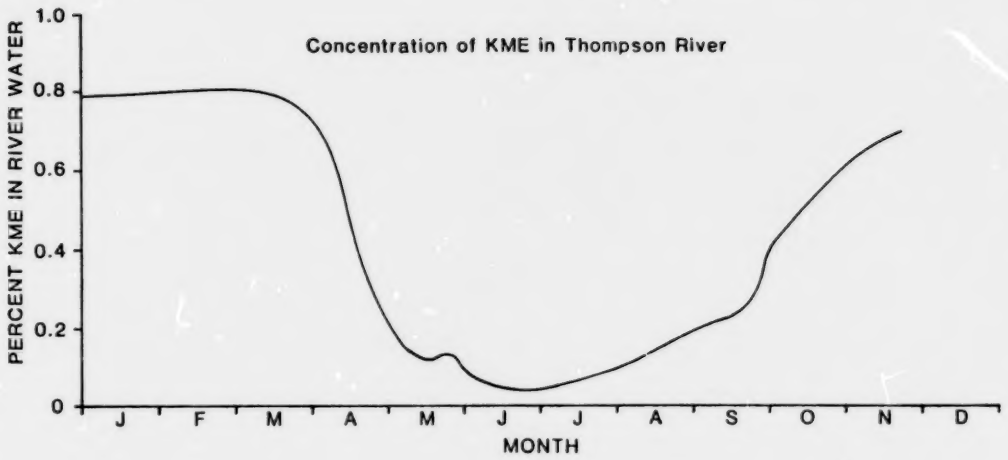

Figure 11. Dilution of the kraft mill effluent (KME) in the Thompson River assuming a steady effluent discharge rate of 1.68 $m^3 \cdot sec^{-1}$ and streamflow data for the Thompson River at Spences Bridge.

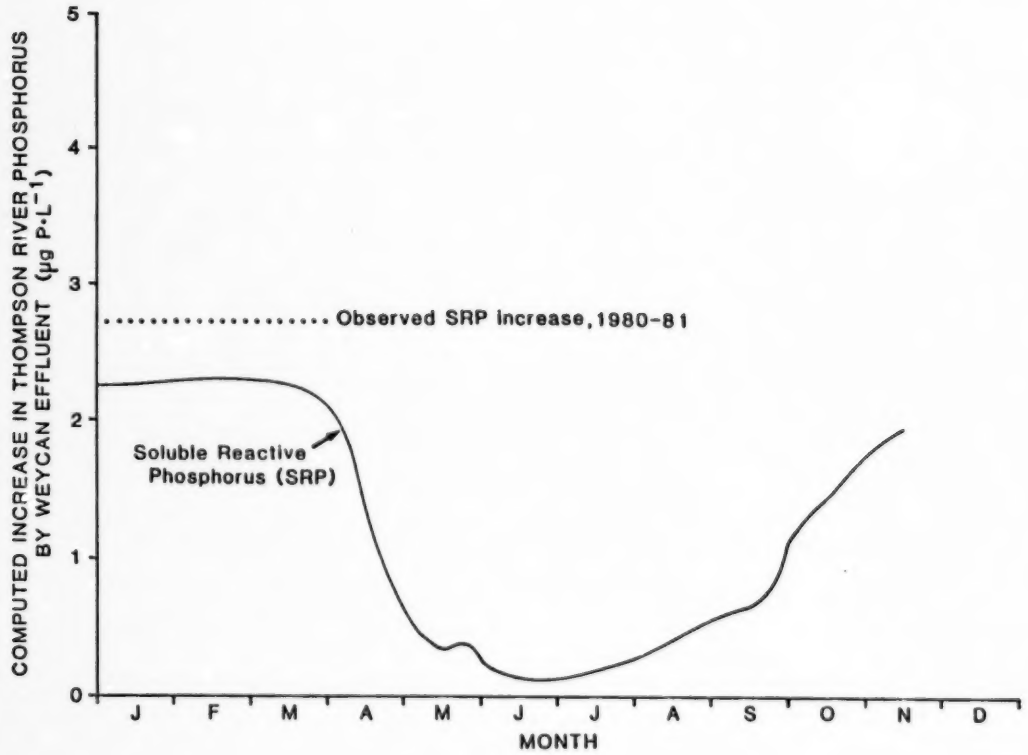

Figure 12. Downstream increases in soluble reactive phosphorus (SRP) due to the discharge of kraft mill effluent to the Thompson River. Computations assume the dilution curve in Figure 11 and an average SRP content of the effluent of 300 ppb.

Data from the long-term biomass accumulation experiment run during high P-deficiency (Figure 5) are replotted in Figure 13 with the data points connected by a smooth curve. Here it can be seen that at present KME loading levels the maximum sustainable algal biomass is raised from 22.3 mg Chl $a \cdot m^{-2}$ to 142.4 mg Chl $a \cdot m^{-2}$. Taking these two values as the natural background level and the present elevated level of algae due to the current P-loading from the KME discharge, respectively, it is possible to calculate the relative improvement from known reductions in the loading. A graphic presentation of this computation is shown in Figure 14. A 50% reduction in the soluble-P output of the pulpmill would be expected to result in less than a 20 percent reduction in algal biomass downstream. To elicit a major reduction in downstream biomass, ie. a 60% decrease in algae, would require a 90% reduction in the current P-loading of SRP from the KME.

There are many assumptions made in the above computations, not the least of which is the validity of extrapolating from experimental troughs to a whole river ecosystem. Still, this attempt to predict the environmental consequences of an altered nutrient loading regime to a river is based on the best scientific data available. Wherever possible environmentally conservative estimates have been used. For example, it was assumed that the background phosphorus levels at the point of mill discharge to the Thompson River are as low as those of the

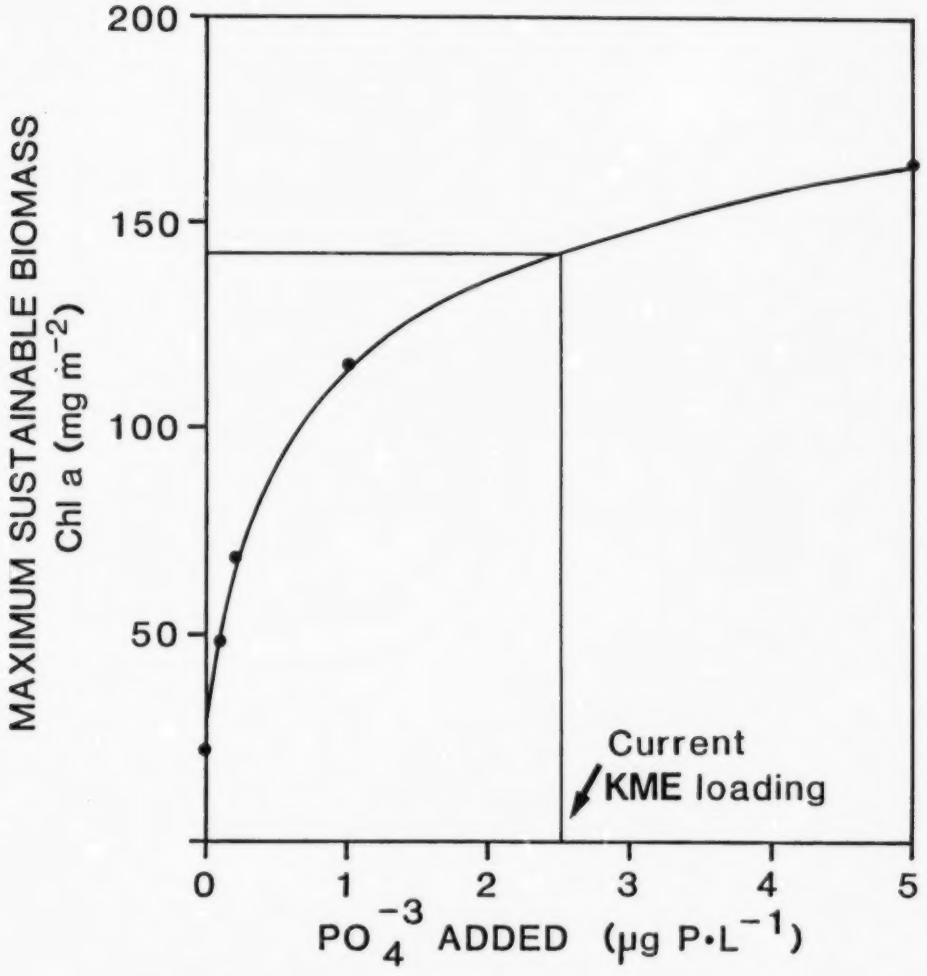

Figure 13. Maximum sustainable algal biomass during high P-limitation period (Feb-Mar) in response to P additions from the KME. The algal biomass resulting from the current KME loading is shown.

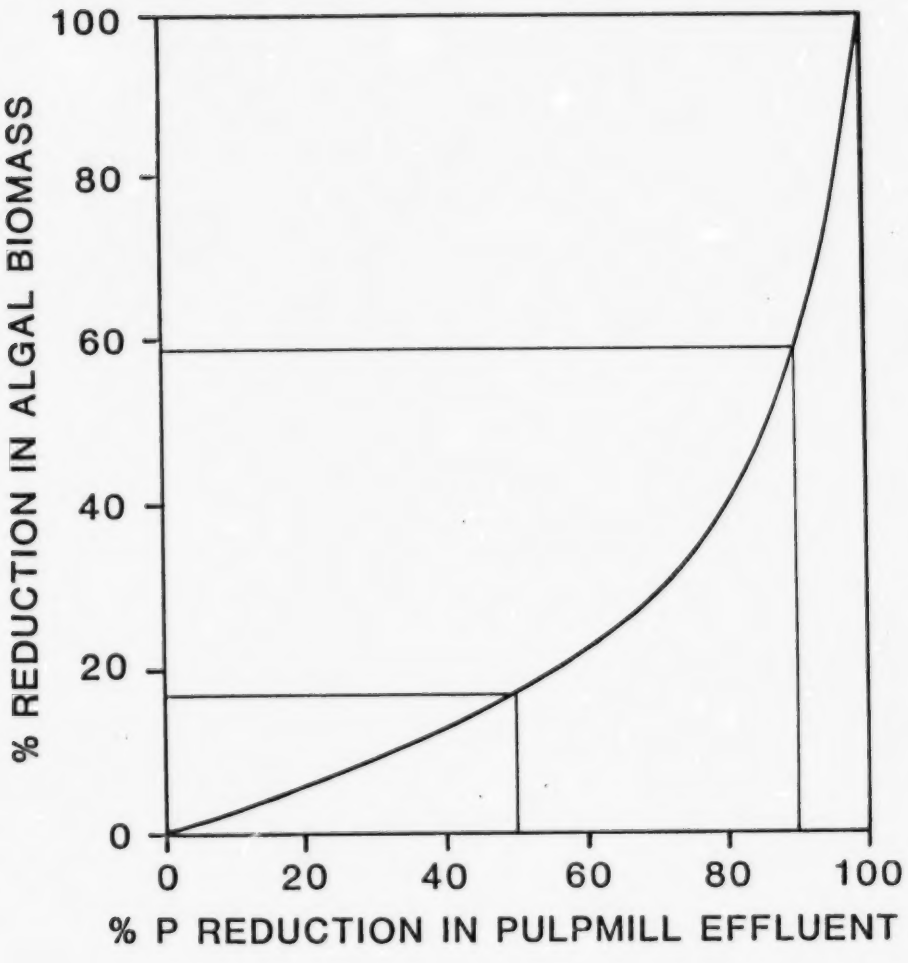

Figure 14. Curve showing on a percentage basis the expected decline in algal biomass as a function of the percentage reduction in soluble available phosphorus from the pulpmill effluent.

South Thompson River near Chase. However, the data from 1980-81 indicated that the background levels of the North Thompson are higher than the South Thompson so the combination of the two rivers must have higher levels than the southern tributary alone.

Another important observation relevant to making decisions about future nutrient control measures on the Thompson River is the general observation that in recent years the massive algal infestations common in the 1970's are no longer occurring. While there is no readily apparent explanation for this, it might be that the invertebrate communities in the river have adapted to the new higher levels of specific production and are now able to keep algal biomass in check. More detailed studies on the invertebrate communities in the river might provide an answer to this important question.

GLOSSARY

specific growth rate (u) The number of divisions per day of a microbial cell. This is a measure of how fast the cells are growing and is independent of how many there are.

maximum specific growth rate, u_{max}. The maximum division rate for cells under the restraints imposed by the physical environment, eg. temperature and light. At this growth rate the cells are not limited by any nutrient and are growing as fast as biologically possible.

relative specific growth rate, $u:u_{max}$. An index of how nutrient deficient the cells are. Their current growth rate (u) divided by the maximum possible growth rate (u_{max}) under the existing physical conditions.

alkaline phosphatase activity (APA) An enzyme produced by many microbial cells in response to phosphorus deficiency. A high level means the cells are P-deficient and a low level means they are P-replete.

chlorophyll (Chl a) A plant pigment used to quantify the amount of algae.

orthophosphate The molecular form of phosphorus which is most readily used by microorganisms.

soluble reactive phosphorus (SRP) Those forms of dissolved phosphorus in water which are measured by standard chemical techniques not using digestion. Most of this is presumed to be orthophosphate.

maximum sustainable algal biomass (MSB) Algal density during long-term (60 day) experiments. Chlorophyll values from Day 35 to the end of each trial were averaged and used as a measure of the maximum amount of algae that could exist per unit surface area under the experimental conditions.

relative maximum sustainable biomass (MSB:MSB_{max-P}). The maximum sustainable biomass (MSB) with existing nutrient levels divided by the MSB at the highest level of enrichment, MSB_{max-P}

REFERENCES

BOTHWELL, M.L. and DALEY, R.J. 1981. Determination of phosphorus sufficiency and growth rates of benthic algae in the Thompson River, B.C. using experimental flowing troughs. IWD Regional report. 32pp.

BOTHWELL, M.L. 1985. Phosphorus limitation of lotic periphyton growth rates: An intersite comparison using continuous-flow troughs (Thompson River system, British Columbia). Limnol. Oceanogr. 30:527-542.

JASPER, S. and BOTHWELL, M.L. 1986. Effects of kraft pulp mill effluent on periphyton in experimental continuous-flow troughs (Thompson River, British Columbia). unpublished report.